

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
<small>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</small> PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 30-08-2007		2. REPORT TYPE Final Technical Report		3. DATES COVERED (From - To) 01-09-2004 - 31/08/2006	
4. TITLE AND SUBTITLE Energy Efficient Transient Plasma Ignition: Physics and Technology				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER FA9550-04-1-0107	
				5c. PROGRAM ELEMENT NUMBER 61102F	
6. AUTHOR(S) Gundersen, Martin A.				5d. PROJECT NUMBER 2308	
				5e. TASK NUMBER TA	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Southern California Electrical Engineering-Electrophysics 3737 Watt Way, PHE 512 Los Angeles, CA 90089-0271				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/NA 875 North Randolph Street Suite 325, Room 3112 Arlington, VA 22203-1768 <i>Dr Julian Tishkoff</i>				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited				AFRL-SR-AR-TR-07-0175	
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The project has conducted basic studies of flame ignition, collaborative studies of pulse detonation ignition, and preliminary studies of fundamental issues relevant to the application of transient plasma as an ignition source for Air Force high-speed aircraft applications. Preliminary basic science experiments have been conducted at the Air Force Research Laboratory (AFRL) using planar laser-induced fluorescence (PLIF) for investigation of radical production and ignition delay. Very strong enhancement of radical species throughout the combustng volume using transient plasma for ignition (TPI) was demonstrated using PLIF, and the production of electronically excited species was well coordinated with TPI. In another study at AFRL systems were interfaced successfully with a pulse detonation engine (PDE), and data were taken for a variety of electrode lengths while burning aviation gasoline and ethylene. The project work also included development of appropriate ignition systems for these studies, comprised of pulse sources, transmission lines (cabling appropriate for nanosecond power pulses), and electrodes, and extending the work from laboratory pulse generation capabilities to considerable reduction in size and weight of the ignition pulse generation. This reduction is a critical issue in the application of this technology. The electrical engineering issues inherent in the application of the short pulses to fuel-air mixtures at various pressures and in a variety of geometries were addressed successfully in the project.					
15. SUBJECT TERMS Transient plasmas, plasma ignition, plasma assisted combustion, flame ignition pulse detonation engine, radical enhancement, nanosecond pulsed power					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES 18	19a. NAME OF RESPONSIBLE PERSON Julian M. Tishkoff
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (include area code) (703) 696-8478

“Energy-Efficient Transient Plasma Ignition: Physics and Technology”

AFOSR Grant No. FA9550-04-1-0107

M. Gundersen, P.I. mag@usc.edu

OBJECTIVES

The objectives of the program are to:

- Conduct experimental studies of transient plasma ignition physics.
- Extend studies of quiescent mixtures to flowing systems.
- Research new pulsed ignition systems.
- Further develop experimental methods for collaborations with the Air Force.
- Integrate transient plasma ignition systems into Air Force experiments.

STATUS OF EFFORT

The project has undergone significant evolution, beginning with basic studies of flame ignition, through collaborative studies of pulse detonation ignition, to current studies of fundamental issues relevant to the application of transient plasma as an ignition source for Air Force applications including scramjets. Preliminary basic science experiments now have been conducted with transient plasma ignition (TPI) at AFRL Propulsion Directorate, Wright Patterson AFB, OH, using planar laser induced fluorescence (PLIF) for investigation of radical production and ignition delay. TPI and pulse generation systems also have been interfaced successfully with the AFRL pulse detonation engine (PDE). In recent work, as an example of studies that show promise for ignition physics in AF applications, a study of flame vs. TPI with Dr. Carter was conducted. Typical ignition with the transient plasma reached peak pressure and almost fully filled the combustion chamber during a time that a conventional spark ignition produced a flame front still close to the back wall of the chamber. The TPI flame front was generated along the length of the TPI anode and propagated radially outward, essentially producing an expanding cylinder of flame versus the characteristic point source of ignition produced by the spark. Very strong enhancement of radical species throughout the volume of TPI was found using PLIF, and the production of electronically excited species was well coordinated with TPI. In another study at AFRL data were taken for a variety of electrode lengths while burning aviation gasoline and ethylene in a PDE. The project work also included development of appropriate ignition systems for these studies, comprised of pulse sources, pulse transmission, and electrodes, and extending the work from laboratory pulse generation capabilities to considerable reduction in size and weight of the ignition pulse generation. Typical pulse parameters for these studies were 20 to 100 nsec pulse voltages up to approximately 90 kV for certain applications, with 60 kV typically matched to the combustion load. These parameters were essential elements in the application of transient plasma, and the electrical engineering issues inherent in the application of the short pulses to fuel-air mixtures at various pressures and in a variety of geometries were addressed successfully. Load matching is a unique aspect of this work that is relevant to future applications of transient plasma.

ACCOMPLISHMENTS/NEW FINDINGS

In work with the PDE, a USC nanosecond pulse generator was interfaced successfully with the AFRL PDE. Data were taken for a variety of electrode lengths while burning aviation gasoline and Ethylene. The data currently being reduced by J. Corrigan from Ohio State University, and should be available this fall. With these data, a correlation may be identified between deposited energy per unit volume and ignition delay. Learning from the experience of experiments conducted earlier in the project (August 2005), the group, in collaboration with Dr. Fred Schauer's group at AFRL, developed a coaxial transient plasma high voltage electrode, Figure 1, that was able to survive the hard environments of a PDE.

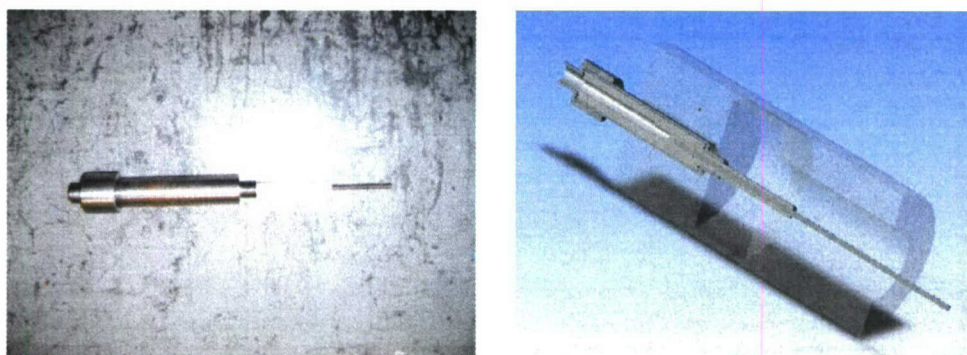


Figure 1. Coaxial electrode developed for the WP PDE.

Trigger board design flaws that did not manifest themselves under single-shot conditions were identified, and a new EMI hardened board for continuous high repetition rate operation is under development. Additionally, the size will be reduced substantially by a factor of 2 or more by potting the high voltage side of the pulse generator.

The transient plasma's ability to fill a volume determined by the electrode geometry gives it a potentially large advantage relative to other ignition sources. This large discharge volume in ignition systems results in multiple ignition kernels, and with shorter ignition delay times and the ability to ignite over a broader range of conditions than a capacitive spark discharge. Figure 2 shows the relative differences between an arc and the transient plasma. The transient plasma occurs over a significantly larger volume than that of the spark. The discharge gap depicted is on the order of 25 mm, using a spark plug for ignition the arc will be on the order of 2-5 mm, essentially a point source.

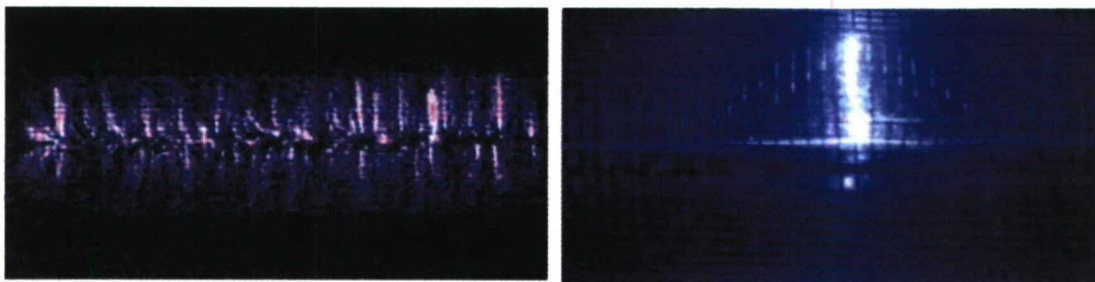


Figure 2. Transient plasma generated in a 2” ID cylindrical mesh (left) and arc (right).

Pulses shorter than 50 ns are essential for further study of transient plasma ignition and streamer physics; therefore, a solid-state long-life pulse generator based on magnetic pulse compression using diodes to sharpen further the pulse was designed and built. Further refinements of the solid state pulse generator have allowed it to reach 80 kV with a 13 ns pulse width at full width half maximum. Development has begun on a high power pulse generator based on magnetic compression that is capable of producing a 100 kV, 50 ns pulse, at 2 kHz. This pulse generator will replace the pseudospark switched pulse generator for many large gap systems. Additionally it will be able to meet requirements for continuous (or pulsed) operation at high repetition rates, whereas the pseudospark switched pulse generator only can operate in a burst mode at 2 kHz. This pulse generator potentially can be used for research into noise reduction, plasma assisted flow control, and scramjet ignition.

Collaboration has begun with Professor Hai Wang from the University of Southern California on modeling the TPI-assisted combustion. The ethylene data taken on the PDE is intended to assist this effort. Additional experiments are scheduled for this fall to determine if the plasma pyrolyzes methane into compounds that ignite more easily (hydrogen, ethylene, etc.).

In collaboration with Dr Cam Carter, AFRL, preparation began for a planar paser induced fluorescence experiment to look at the radicals produced by the transient plasma. OH production was studied, however, additional experiments to look at NO, and atomic O were scheduled. Additionally a high speed camera was scheduled for use to image flame propagation for the transient plasma ignition case (800 mJ) and for a traditional spark ignition case (40 mJ). The experiment took place 4-17 March 2007. While the data have not been processed fully yet, we do see some interesting results. Figure 3 depicts the combustion chamber that was designed for this experiment. The main imaging window is 10.16 cm diameter, 2.54 cm thick fused silica, and the laser entrance and exit windows are 2.54 cm diameter sapphire. The chamber is 10.16 cm inner diameter, 20.32 cm long stainless steel. The anode was an 8-32 threaded rod, approximately 7.62 cm long.

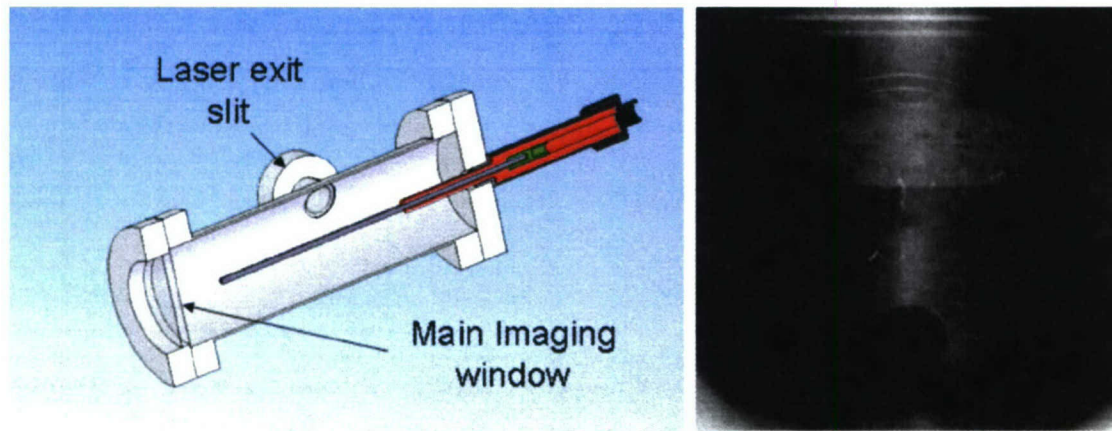


Figure 3: Cross-section of a 4" ID, 8" long combustion chamber (left). Field of view for high speed camera (right).

Figure 4 depicts the high speed camera results (500 $\mu\text{s}/\text{frame}$) from one of the runs. At 50 ms, the transient plasma almost had reached peak pressure and had an almost full mixture in the chamber, whereas in the case of the spark, the flame front barely has left the back wall of the chamber ($\sim 2"$ from the point of origin). What is not apparent in this picture is that the TPI flame front always was generated along the length of the anode and propagated radially outward, essentially producing an expanding cylinder of flame, versus the point source of ignition produced by the spark.

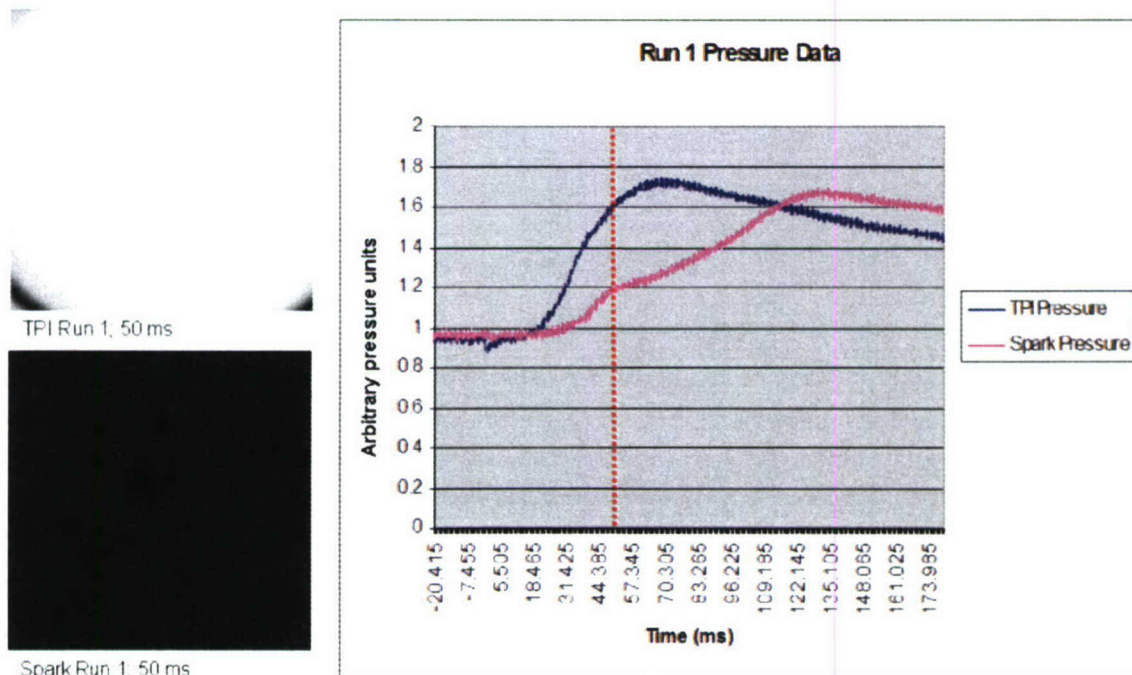


Figure 4: Flame produced via TPI and spark ignition of CH_4 – air, $\phi = 1$, at $t = 50$ ms (left). Associated pressure traces (right).

The OH-PLIF experiment confirmed radical production over the discharge volume. The OH-PLIF measurement will be excited via $A^2\Sigma^+ \rightarrow X^2\Pi(1,0)$ band OH near 283nm. As seen in Figure 5 the OH produced appears to have followed the initial streamer path; however, as these are shot-to-shot images, this is an inferred result. The OH produced seems to drop below the detection limit of the experiment after about 100 μs , and nothing is seen until ignition along the anode occurs at ~ 5 ms; however, when looking at the high speed camera images as the flame propagates outward toward the chamber wall, multiple ignition kernels are seen clearly.

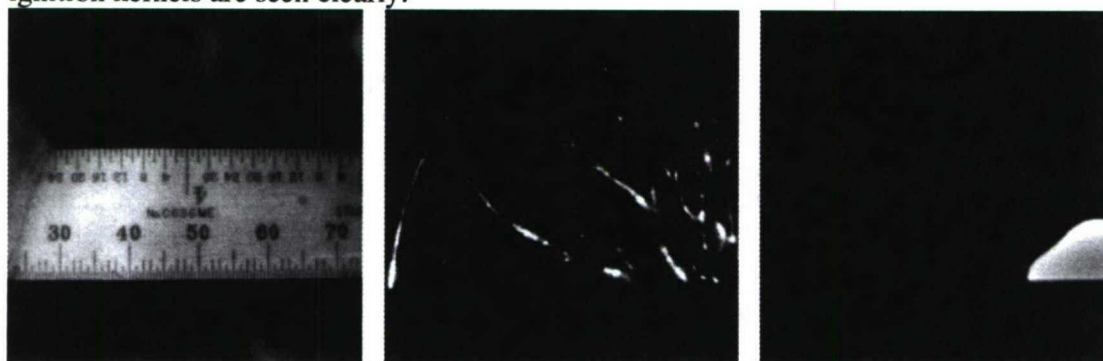


Figure 5: Field of view for PLIF in CH_4 – air, $\phi = 1$ (left). OH at $t = 2.064 \mu\text{s}$ (center), and OH produced via ignition at $t = 5$ ms (right).

An interesting follow on to this experiment is to see how radical production scales with a reduced electric field and the effect of water vapor on OH production. Additionally, the experiment could be set up concurrent with a filtered Rayleigh scattering or two line OH measurement to determine radical temperature, thus giving us the ability to determine both the mole fraction and number density of OH created.

Once ignition of the supersonic flow is achieved, the flame is self-sustaining under the proper speed and pressure conditions; however, there is the possibility that flame blow-off will occur, and reliable relight of the engine is required. For a flyable system, a secondary supply of gas can act as the aerodynamic restrictor, or an accelerant like silane can be used to facilitate the ignition process; however, these technologies increase system weight and complexity and introduce serious safety issues (silane reacts explosively with air), and there are issues with the reliability in that they allow for a limited number of ignition attempts, as well as a probable few, if any, re-light attempts. In order to obtain combustion of high speed flows it is important that the streamer velocity be as high as possible. Typical streamer velocities in air range from 10^7 - 10^9 cm/sec and may be fast enough to have applications for supersonic combustion in aircraft engines, which occurs in hypersonic platforms like a scramjet. If operated in a high repetition rate mode, the transient plasma may be able to deposit enough energy into the flow for ignition.

Development of a compact, high repetition rate pulse generator for transient plasma ignition continued, with primary focus on decreasing the size and weight and increasing the reliability and life, both criteria essential for practical deployment in application. Field testing of the 2005 pulse generator design was accomplished, and areas of needed improvement were identified, specifically an electromagnetic interference hardened triggering circuit, as well as the need to stabilize performance under different operating

humidity and pressure conditions. The ultimate goal is improved performance for continuous operation and reduction in size of the pseudospark-based pulse generator and rapid charger system. The alternate architecture of a fully solid-state, long-life pulse generator was also further refined, reaching higher operating voltages while still maintaining its pulse integrity. Continuing the development of miniature pseudospark switches for reliable and long-life operation of transient plasma ignition systems, an optically triggered switch (BLT) with an inverse dependence on electrode area and hold-off voltage was found.

Studies of transient plasma ignition of Pulse Detonation Engines were successfully extended to flowing mixtures and significant repetition rates in collaboration with Dr. C. Brophy and Dr. J. Sinibaldi at the Naval Postgraduate School Laboratory in Monterey, CA. Studies at Wright Patterson Air Force Research Laboratory in collaboration with Dr. F. Schauer and his research group for application to Air Force pulse detonation engines have also been conducted (July 2006), for which a coaxial high voltage transient plasma electrode which interfaces with a 14mm sparkplug feedthrough in its PDE was developed and successfully tested. The preliminary results confirm last year's AVGAS data.

INTERACTIONS WITH AFRL LABORATORY RESEARCHERS

Transient plasma ignition was successfully applied to Pulse Detonation Engine research with Dr. Fred Schauer of AFRL/PRTC at Wright-Patterson AFB. A pseudospark pulse generator with HV DC power supply was installed on a PDE experiment by Mr. Charles Cathey. Collaborative studies are under way with Stanford University (Hanson) for the purpose of integrating optical diagnostics for the purpose of understanding ignition-related plasma physics.

July 9-13, 2006, studies were conducted at AFRL with collaboration between USC (C. Cathey, M.G.) and Dr. F. Schauer's PDE research group. These studies included first tests in the AFRL apparatus with aviation fuel and separately with ethylene over a variety of electrode lengths, in order to determine a correlation between energy/volume delivered and ignition delay. Additionally, a new electrode was developed and integrated successfully with the PDE. Data reduction is incomplete at this point and will be available later this fall. Preliminary results with aviation gasoline look to confirm the data taken in August 2005. Tentatively, a factor of two (2) reduction in delay was observed in AvGas. Improved lean-burn operation was also achieved.

Dr. Carter at AFRL and C. Cathey discussed a laser induced fluorescence (LIF) experiment for the spring of 2007. The experiment would look primarily at OH and to a lesser extent at NO, and O, and attempt to determine the relative intensities of these species produced in a transient plasma discharge, the interesting aspect being the time interval between application of the transient plasma and the occurrence of flame. In addition, the ability to resolve spatially and temporally the production of said species will assist in the development of a model for transient plasma ignition greatly. The plan for a two week experiment is to provide a chamber and electrode system and for Dr. Carter to provide the optical diagnostics and fuel.

A summary abstract reviewing the tests at various laboratories, including AFRL and NPS, which illustrates the interactions with AFRL researchers, has been submitted for presentation at the January Reno AIAA meeting and is attached as an Appendix.

PERSONNEL SUPPORTED

Professor Martin Gundersen	Professor
Dr. Andras Kuthi	Research Scientist
Dr. Fei Wang	Graduate Research Assistant (completed PhD)
Mr. Charles Cathey	Graduate Research Assistant
Mr. Tao Tang	Graduate Research Assistant

PUBLICATIONS

A. Journal Papers

C. Jiang, A. Kuthi, and M. A. Gundersen, “Toward ultracompact pseudospark switches” *Appl. Phys. Lett.* Vol. **86**, 024105 (2005).

J.B. Liu, F. Wang, G. Li, A. Kuthi, E. J. Gutmark, P.D. Ronney, and M.A. Gundersen, “Transient Plasma Ignition,” *IEEE Transactions on Plasma Science*, Vol. 33, No. 2, April 2005.

F. Wang, J.B. Liu, J. Sinibaldi, C. Brophy, A. Kuthi, C. Jiang, P. Ronney, and M.A. Gundersen, “Transient Plasma Ignition of Quiescent and Flowing Air/Fuel Mixtures,” *IEEE Transactions on Plasma Science*, Vol. 33, No. 2, April 2005.

F. Wang, A. Kuthi, and M.A. Gundersen, “Compact High Repetition Rate Pseudospark Pulse Generator,” *IEEE Trans. Plasma Science*, accepted for publication 2005.

B. Papers in Conference Proceedings

C. Cathey, F. Wang, T. Tang, A. Kuthi, M.A. Gundersen, J. Sinibaldi, C. Brophy, J. Hoke, F. Schauer, J. Corrigan, J. Yu, E. Barbour, and R. Hanson, “Transient Plasma Ignition for Delay Reduction in Pulse Detonation Engines,” 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 2007, TBP.

H. Chen, C. Jiang, A. Kuthi, and M.A. Gundersen, “Small Size Back Lighted Thyatron,” EAPPC 2006, Chengdu, China, 18-22 September 2006, TBP.

P. Hutcheson, C. Brophy, J. Sinibaldi, C. Cathey, and M.A. Gundersen, “Investigation of Flow Field Properties on Detonation Initiation,” 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference 2006, Sacramento, California, 9 -12 July 2006.

F. Wang, C. Cathey, A. Kuthi, T. Tang, H. Chen, and M.A. Gundersen, “Pseudospark Based Power Modulator technology for Transient Plasma Ignition,” 27th International Power Modulator Conference 2006, Washington, D.C., 14-18 May 2006.

T. Tang, A. Kuthi, F. Wang, C. Cathey, and M.A. Gundersen, “Design of 60kV 20ns solid state pulse generator based on magnetic reactor driven diode opening switch,” 27th International Power Modulator Conference 2006, Washington, D.C., 14-18 May 2006.

H. Chen, A. Kuthi, and M.A. Gundersen, “High voltage, Back-Lighted Thyatron,” 27th International Power Modulator Conference 2006, Washington, D.C., 14-18 May 2006.

F. Wang, A. Kuthi, C. Jiang and M. Gundersen, “Technology for Transient Plasma Ignition,” 43rd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan. 10-13, 2005. AIAA Paper 2005-0951.

D. Lieberman, J. Shepherd, F. Wang and M. Gundersen, “Characterization of a Corona Discharge Initiator Using Detonation Tube Impulse Measurements,” 43rd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan. 10-13, 2005. AIAA Paper 2005-1344.

F. Wang, M.A. Gundersen, A. Kuthi, and T. Tang, “Technology for Transient Plasma Ignition,” 2005 ONR Review, August 24-26, 2005, Naval Postgraduate School, CA.

F. Wang, T. Tang, C. Cathey, A. Kuthi, and M. Gundersen, “Solid-state High Voltage Nanosecond Pulse Generator,” Proceedings of the 15th International Pulsed Power Conference, Monterey, CA, June 13-17, 2005.

INTERACTIONS/TRANSITIONS

A. PARTICIPATION/PRESENTATIONS AT MEETINGS, CONFERENCES, SEMINARS, ETC.

C. Cathey, F. Wang, T. Tang, A. Kuthi, M.A. Gundersen, J. Sinibaldi, C. Brophy, J. Hoke, F. Schauer, J. Corrigan, J. Yu, E. Barbour, and R. Hanson, “Transient Plasma Ignition for Delay Reduction in Pulse Detonation Engines,” 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 2007.

H. Chen, C. Jiang, A. Kuthi, and M.A. Gundersen, “Small Size Back-Lighted Thyatron,” EAPPC 2006, Chengdu, China, 18-22 September 2006, TBP.

P. Hutcheson, C. Brophy, J. Sinibaldi, C. Cathey, and M.A. Gundersen, “Investigation of Flow Field Properties on Detonation Initiation,” 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference 2006, Sacramento, California, 9-12 July 2006.

F. Wang, C. Cathey, A. Kuthi, T. Tang, H. Chen, and M.A. Gundersen, “Pseudospark Based Power Modulator Technology for Transient Plasma Ignition,” 27th International Power Modulator Conference 2006, Washington, D.C., 14-18 May 2006.

T. Tang, A. Kuthi, F. Wang, C. Cathey, and M.A. Gundersen, “Design of 60kV 20ns solid state pulse generator based on magnetic reactor driven diode opening switch,” 27th International Power Modulator Conference 2006, Washington, D.C., 14-18 May 2006.

H. Chen, A. Kuthi, M.A. Gundersen, “High Voltage, Back-Lighted Thyatron,” 27th International Power Modulator Conference 2006, Washington, D.C., 14-18 May 2006.

“Technology for Transient Plasma Ignition,” F. Wang, A. Kuthi, C. Jiang and M. Gundersen, 43rd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan. 10-13, 2005. AIAA Paper 2005-0951.

“Characterization of a Corona Discharge Initiator Using Detonation Tube Impulse Measurements,” D. Lieberman, J. Shepherd, F. Wang and M. Gundersen, 43rd AIAA

Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan. 10-13, 2005. AIAA Paper 2005-1344.

“Paschen Characteristics of the Pseudospark Discharge,” A. Kuthi and M. Gundersen, abstract for 32nd International Conference on Plasma Science (2005 ICOPS), Monterey, CA, June 19-23, 2005.

“Paschen Characteristics of the Pseudospark Discharge,” A. Kuthi and M. Gundersen, poster presentation for 32nd International Conference on Plasma Science (2005 ICOPS), Monterey, CA, June 19-23, 2005.

“Solid-state High Voltage Nanosecond Pulse Generator,” F. Wang, T. Tang, C. Cathey, A. Kuthi, and M. Gundersen, Proceedings of the 15th International Pulsed Power Conference, Monterey, CA, June 13-17, 2005.

“Technology for Transient Plasma Ignition,” F. Wang, M.A. Gundersen, A. Kuthi, and T. Tang, 2005 ONR Review, August 24-26, 2005, Naval Postgraduate School, CA.

B. CONSULTATIVE AND ADVISORY FUNCTIONS TO OTHER LABORATORIES AND AGENCIES

Visiting Prof. in the Physics Department at the Naval Postgraduate School (NPS) during June 2006. Studies of the transient plasma ignition were conducted in the valveless PDE at NPS.

C. TRANSITIONS. DESCRIBE CASES WHERE KNOWLEDGE RESULTING FROM YOUR EFFORT IS USED, IN A TECHNOLOGY APPLICATION.

The transient plasma ignition is being utilized for further development of the Navy’s PDE. Researchers at NPS have indicated that they view transient plasma ignition as “enabling”. Interest in applying this approach by such commercial engine companies including GE Global, Volvo, Nissan, and others has been expressed. Nissan is exploring the application for high compression internal combustion engines.

TWO APPENDICES ARE ATTACHED.

Attached as Appendix A is a summary of research necessary to enable technology supporting the implementation of TPI.

Attached as Appendix B is an extended abstract from the 45th AIAA Aerospace Sciences meeting that summarizes collaborative research and results of PDE studies using TPI:

C. Cathey, F. Wang, T. Tang, A. Kuthi, M. A. Gundersen, J. Sinibaldi, C. Brophy, J. Hoke, F. Schauer, J. Corrigan, J. Yu, E. Barbour, and R. Hanson, “Transient Plasma Ignition for Delay Reduction in Pulse Detonation Engines,” 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 8-11 Jan 2007.

APPENDIX A

Currently, one of the approaches being pursued to advance the group's pulse generator technology is improvement upon the pseudospark switch. These improvements have manifested in the development of a high voltage, fast rise current time, compact, long life time switch that can replace the pseudospark. The switch is a Back Lighted Thyatron (BLT). The BLT, as seen in Figure 6, is a laser-triggered (can be electrically triggered also) hollow cold cathode thyatron, is able to switch 40 kV, 9 kA, with a rise time of less than 20 ns, and is about a third the size of the FS2000 pseudospark switch currently in use. Typical data are shown in Figure 7. The switch was operated in an optically triggered mode (BLT) with helium fill for $>10^6$ pulses and 0.5 mC transfer per pulse at a repetition rate of 10 Hz without significant decay of switch performance. Operation in hydrogen and electrically triggered pseudospark mode was conducted as well. An inverse relationship between electrode cross section and hold-off voltage also was determined. Studies to determine the hold off voltage for a given geometry were limited by the setup, as arc-over would occur at 40 kV prior to switch breakdown. These studies suggest that the small pseudospark/BLT is a potential compact replacement for the large pseudospark switches currently used in repetitive pulsed power applications, such as transient plasma based ignition and combustion control systems.

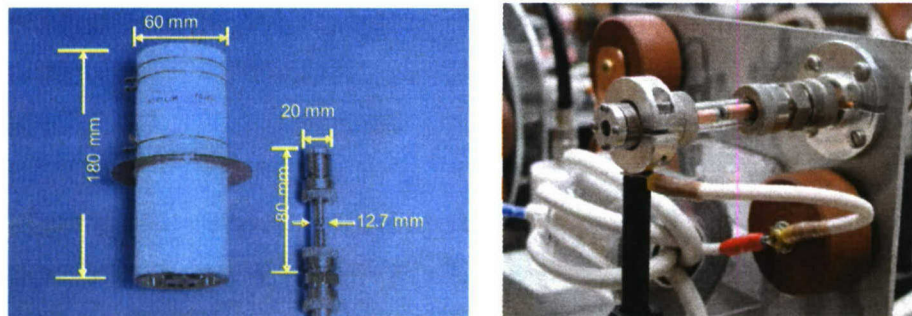


Figure 6. A commercial sealed Pseudospark and the compact BLT switch. The small BLT has similar characteristics to the large one. On the right: the compact BLT switch mounted in the Blumlein pulse generator.

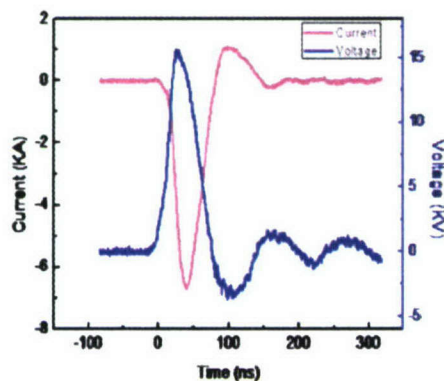


Figure 7. Voltage and current waveforms across the compact BLT switch.

The solid state opening switch (SOS) pulse generator takes a long, relatively low voltage pulse and compresses it through a series of LC resonant stages. What is novel in this architecture is that a diode chain is used to sharpen the final output pulse. The advantage of this pulse generator is that it potentially can deliver more energy into a smaller gap than the pseudospark pulse generator. Immediate applications are internal combustion engines and smaller gap PDEs. To date, research indicates that for small gap systems, this type of system can perform better than the pseudospark pulse generator because it deposits more energy prior to arcing. The caveat is that, due to the solid state pulse generator's short pulse width, for a large gap system, the output pulse voltage needs to be approximately 1.5 times the pseudospark pulse generator's output pulse voltage to perform on the same level. Resulting insulation requirements can become a limiting factor in making a pulse generator of this architecture a compact ignition system for large gaps. Figure 8 depicts the circuit diagram for this pulse generator. Figure 9 illustrates the relative sizes of both the pseudospark switched pulse generator and the magnetic compression pulse generator.

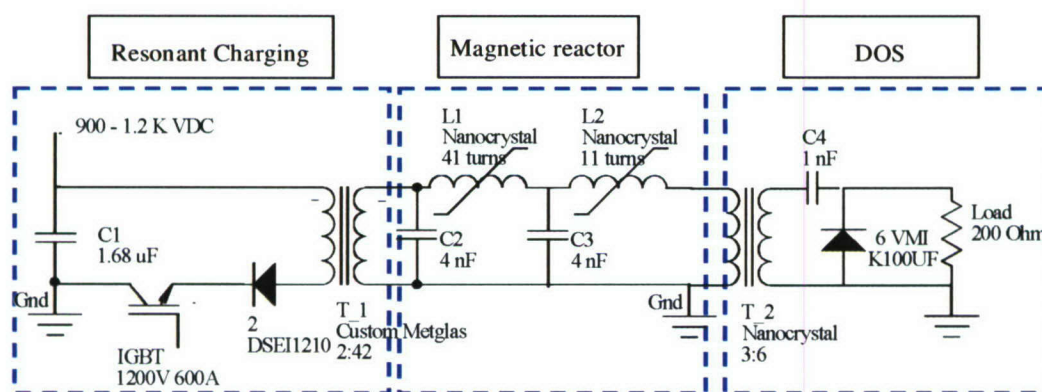


Figure 8: SOS pulse compression pulse generator.

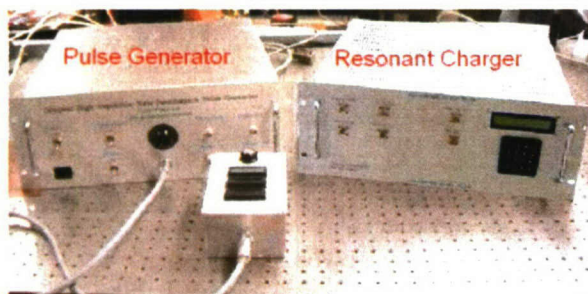


Figure 9: Pseudospark pulse generator and resonant charger (left), magnetic pulse compression pulse generator w/ pulse sharpening (right).

Currently, the solid state pulse generator is not able to operate efficiently at the repetition rates needed for PDEs. The limited repetition rate is not a fault of the pulse generator but is due to the need for a strong current source. A rapid charger is being developed that will be able to fulfill the current to drive the solid state pulse generator under high frequency operation.

The high repetition rate magnetic compression pulse generator that is under development has a similar architecture to the SOS pulse generator in Figure 8. The major differences are that the insulated gate bipolar transistor is being replaced with a much cheaper silicon controlled rectifier, and there are no diodes used to sharpen the pulse. This pulse generator is expected to be completed in early summer 07.

APPENDIX B

Attached is a copy of C. Cathey, F. Wang, T. Tang, A. Kuthi, M. A. Gundersen, J. Sinibaldi, C. Brophy, J. Hoke, F. Schauer, J. Corrigan, J. Yu, E. Barbour, and R. Hanson, “Transient Plasma Ignition for Delay Reduction in Pulse Detonation Engines,” 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 8-11 Jan 2007.

Transient Plasma Ignition for Delay Reduction in Pulse Detonation Engines

Charles Cathey, Fei Wang, Tao Tang, Andras Kuthi, and Martin A. Gundersen
University of Southern California, Los Angeles, Ca 90089

Jose O. Sinibaldi, and Chris Brophy
Rocket Propulsion Laboratory, Naval Postgraduate School, Monterey, Ca 93943

John Hoke and Fred Schauer
Air Force Research Laboratory, Propulsion Directorate, Wright-Patterson AFB, OH 45433

Jennifer Corrigan and John Yu
Ohio State University, Columbus, OH 43210

Ethan Barbour, and Ronald K. Hanson
Stanford University, Palo Alto, Ca 94305

Abstract— This presentation reviews testing and evaluation at four laboratories of transient plasma for pulse detonation engine (PDE) ignition, and presents data showing significant reductions in times required for detonation. The aerospace community has ongoing interests in the development of propulsion technologies based on pulse detonating engines (PDE), and work is underway to determine whether this is a feasible technology. The PDE provides impulse through fuel detonation, and potential advantages include efficient operation at both subsonic and supersonic speeds. In theory a PDE can efficiently operate from Mach 0 to more than Mach 4 [1,2]. In order to achieve almost continuous thrust firing rates of 100 Hz or more are needed. Critical to achieving high repetition rates are minimal delay to detonation times. In work supported by the Office of Naval Research and the Air Force Office of Scientific Research, transient plasma ignition (TPI) has consistently shown substantial reductions in ignition delay time for various fuels [3,4,5]. Experiments have been conducted at the University of Southern California and in collaboration with researchers at the Naval Postgraduate School, Wright Patterson Air Force Research Laboratory, Stanford University, the University of Cincinnati, and California Institute of Technology [6]. In these studies it was observed that TPI significantly reduces delay times in both static and flowing systems. Transient plasma ignition is attractive as an ignition source for PDEs because it produces reductions in ignition delay times, can reduce Deflagration to Detonation Transition (DDT) times, and has been shown to provide the capability to ignite under leaner conditions. This allows for high repetition rates, high altitude operation, and reduced NO_x emissions [7,8]. The geometry of the discharge area is such that ignition is achieved with a high degree of spatial uniformity over a large volume relative to traditional spark ignition. The short timescale of the pulse (< 100 ns) prevents formation of an arc, and a voluminous array of streamers is used for ignition. It is possible that energetic electrons in the highly non-equilibrated electron energy distribution of the streamers cause dissociation of hydrocarbon chain molecules, producing active radicals throughout the ignition volume [9]. A further advantage of TPI is that a smaller fraction of the electrical energy goes into thermal heating of the mixture. These effects allow for large numbers of active species to be generated throughout the volume.

Figure 1 shows data taken in collaboration with Professor Hanson's group at Stanford University. The different levels of OH indicate a potentially new combustion pathway of transient plasma ignition. Currently the physics behind transient plasma ignition is poorly understood, however, work is underway to better understand this process.

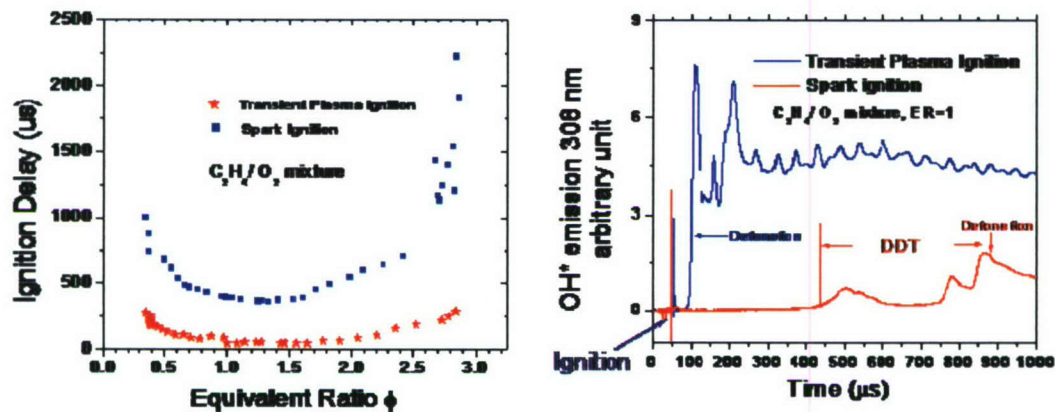


Figure 1

Ignition delay (left) and OH emission (right) in Stanford PDE. TPI enabled a factor of 9 reduction in delay to detonation.

The igniter operates reliably in repetitive modes with pulse lengths typically between 50 ns and 75 ns. In some situations with the appropriate shielding and grounding it will operate with less electromagnetic interference than conventional spark ignition. A summary of experiments conducted with multiple laboratories is seen in Figure 2. These experiments demonstrated considerable reduction in delay to detonation, and improvement in repetition rate, while retaining low energy cost.

The experiments were under varying conditions, and in each case a dramatic reduction in delay was observed. The results suggest a potential solution to one of the most serious limitations to the development of PDEs. Desired pulse amplitude depends on the exact geometry of the combustor, ignition chamber as well as corona electrode. Typical voltages employed are 50 kV – 70 kV for these studies, with pulse energies of the order 100 mJ to 1.16 J depending on how well matched the ignition system is to the load. The ignition system typically consists of a pseudospark based pulse generator, a rapid charger or HV DC supply, and an electrode interface assembly [10, 11].

	Lab	Fuel	Oxidizer	Ignition Delay (msec)	DDT (msec)	Energy Delivered (Joules)
TPI	Stanford	C2H4	O ₂	0.05	0.05	1.16
Spark	Stanford	C2H4	O ₂	0.5	0.45	?
TPI	NPS	C2H4	Air		2	0.3
Spark	NPS	C2H4	Air		8	0.2
TPI	WPAFB	AVGAS	Air	6	2.25	0.67
Spark	WPAFB	AVGAS	Air	10	1.7	?
TPI	WPAFB	AVGAS	Air	5	2.5	0.87
Spark	WPAFB	AVGAS	Air	10	1.7	?
TPI	WPAFB	H2	Air	0.4	0.57	0.67
Spark	WPAFB	H2	Air	0.51	0.61	?
TPI	WPAFB	H2	Air	0.3	0.67	0.87
Spark	WPAFB	H2	Air	0.51	0.61	?

Figure 2

Transient Plasma Ignition results.

Research directed towards more compact versions of the pulse generation technology to ensure it is a viable option for airborne platforms and for use in other applications, is briefly discussed. A miniaturized

back-lighted thyatron (BLT) switch is to be discussed as a feasible replacement for the relatively large pseudospark switch [12]. The BLT is a laser triggered (can be electrically triggered also) hollow cold cathode thyatron and is able to switch 40 kV, 9 kA. The other methodology we are exploring is to entirely replace the pseudospark/lumped Blumlein architecture with a pulse generator based on magnetic compression (solid state pulse generator) [13]. This pulse generator takes a long relatively low voltage pulse and compresses it through a series of LC resonant stages. What is novel in this architecture is that a diode chain is used to sharpen the final output pulse. Currently this pulse generator is capable of producing a 20 ns pulse of 60 kV. The advantage of this pulse generator is that it can potentially deliver more energy into a gap prior to breakdown than the pseudospark pulse generator. Additionally the solid state pulse generator is greatly reduced in size and weight relative to the current pseudospark based pulse generator that was used for the data reported in this conference. An immediate application for the solid state pulse generator is internal combustion engines, and smaller gap PDEs. To date our research indicates for small gap systems this type of system can perform better than the pseudospark pulse generator because it can deposit more energy prior to arcing. The caveat to that is due to the solid state pulse generators short pulse width, for a large gap system the output pulse voltage needs to be approximately 1.5 times the pseudospark pulse generator's output pulse voltage to perform on the same level, resulting in higher insulation requirements.

Based on these studies, transient plasma ignition is potentially an enabling technology for pulse detonating engines. The reduction in ignition delay times allows for higher repetition rates, and improved lean burn operation.

Key Figures:

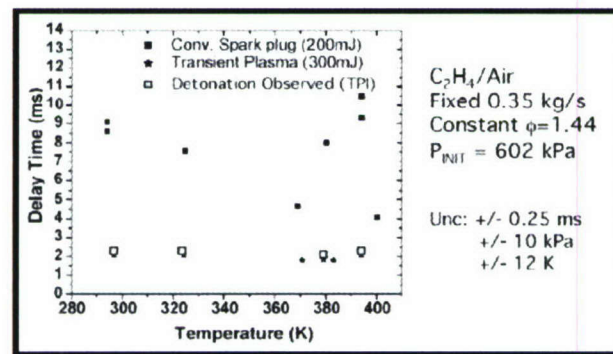


Figure 3
 C_2H_4 Ignition Delay
 USC-NPS

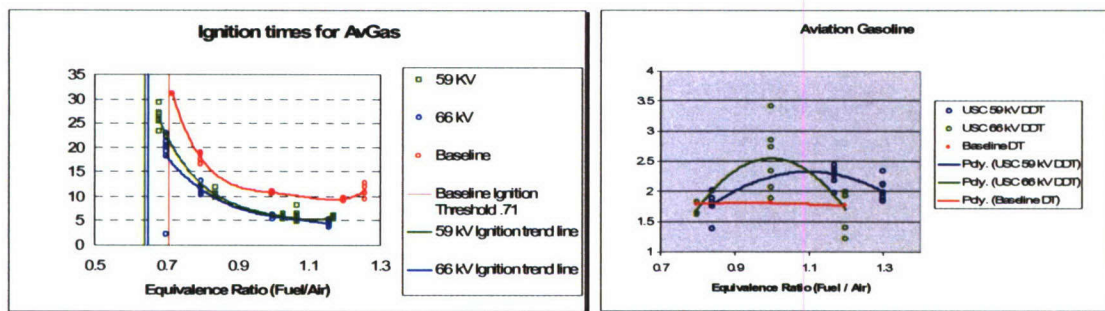


Figure 4
AVGAS Data
USC-WPAFB

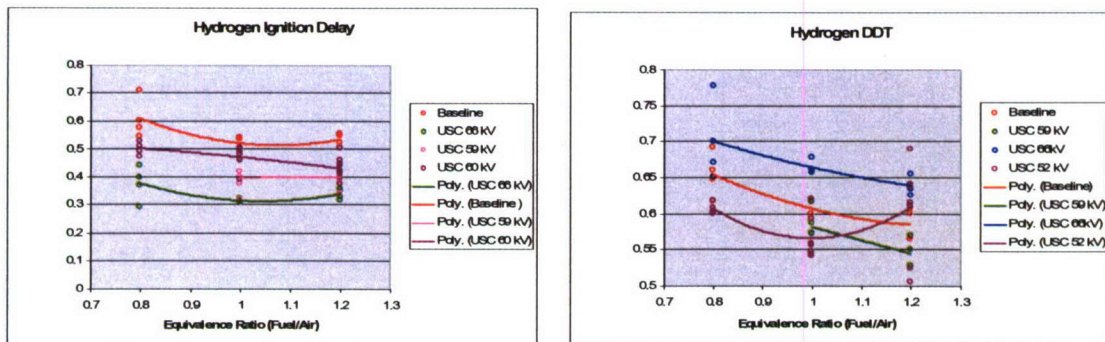


Figure 5.
H₂ Data
USC-WPAFB

Acknowledgements

This work was supported by grants from the Air Force Office of Scientific Research and the Office of Naval Research.

References

- [1] P. G. Harris, R. A. Stowe, R. C. Ripley, and S. M. Guzik, "Pulse Detonations Engine as a Ramjet Replacement," AIAA-2006-462, Vol. 22, No. 2, March–April 2006.
- [2] T. R. A. Bussing, T. E. Bratkovich, and J. B. Hinkey Jr., "Practical Implementations of Pulse Detonation Engines," AIAA-1997-2748 AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 33rd, Seattle, WA, July 6-9, 1997.
- [3] F. Wang, J. B. Liu, J. Sinibaldi, C. Brophy, A. Kuthi, C. Jiang, P. Ronney, and M. A. Gundersen, "Transient plasma ignition of quiescent and flowing air/fuel mixtures," IEEE Transactions on Plasmas, Volume: 33, Issue: 2, Part 2 April 2005, Pg 844-849.
- [4] S. M. Starikovskaia, I. N. Kosarev, A. V. Krasnochub, E. I. Mintoussov, and A. Yu. Starikovskii, "Control of Combustion and Ignition of Hydrocarbon-Containing Mixtures by Nanosecond Pulsed Discharges," AIAA , AIAA-2005-1195, 43rd AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 10-13, 2005.

- [5] J. O. Sinibaldi, J. Rodriguez, B. Channel, C. Brophy, F. Wang, C. Cathey, and M. A. Gundersen, "Investigation of transient Plasma Ignition of Pulsed Detonation Engines," AIAA, AIAA-2005-3774, 41st Joint Propulsion Conference and Exhibit, Tucson, Arizona, July 10-13 2005.
- [6] D. Lieberman, J. Shepherd, F. Wang and M. Gundersen, "Characterization of a Corona Discharge Initiator Using Detonation Tube Impulse Measurements," 43rd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan. 10-13, 2005. AIAA Paper 2005-1344.
- [7] S. A. Bozhenkov, S. M. Starikovskaya, and A. Yu. Starikovskii, Combustion and Flame, 133(2003) 133-146.
- [8] S. M. Starikovskia, E. N., Kukaev, and A. Yu. Kuksin, Combustion and Flame 139 (2004) 177-187.
- [9] B. N. Ganguly, and J. W. Parish, "Absolute H atom density measurement in pure methane pulsed discharge," Applied Physics Letters, Vol. 84, No. 24, June 2004.
- [10] F. Wang, A. Kuthi, and M. A. Gundersen, "Compact High Repetition Rate Pulse Generator," IEEE Transactions on Plasma Science, Volume: 33, Issue: 4, Part 1, Aug. 2005, pg 1177-1181.
- [11] F. Wang, A. Kuthi, C. Jiang, Q. Zhou, and M.A. Gundersen, "Flyback Resonant Charger for High Repetition Rate Pseudospark Pulse Generator," 26th IEEE International Power Modulator Conference, San Francisco, CA, May 23-26, 2004
- [12] H. Chen, A. Kuthi, M. A. Gundersen, "High voltage, Back-Lighted Thyatron," 27th International Power Modulator Conference 2006, Washington D. C., District of Columbia, May 14-18th, 2006.
- [13] T. Tang, A. Kuthi, F. Wang, C. Cathey, and M. A. Gundersen, "Design of 60kV 20ns solid state pulse generator based on magnetic reactor driven diode opening switch," 27th International Power Modulator Conference 2006, Washington D. C., District of Columbia, May 14-18th, 2006.